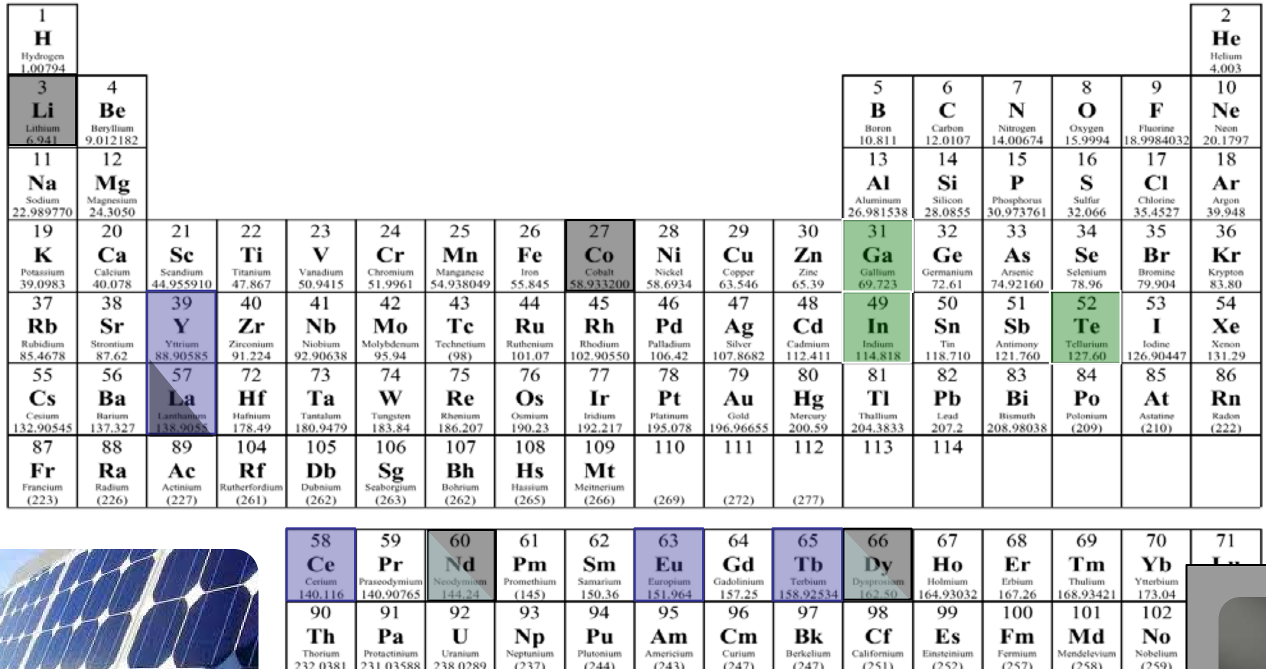
Critical Materials:
Rare Earth & Related Elements

Mark Johnson

February 28, 2011

Critical Materials in Clean Energy



Vehicles

Lighting

Solar PV

Wind

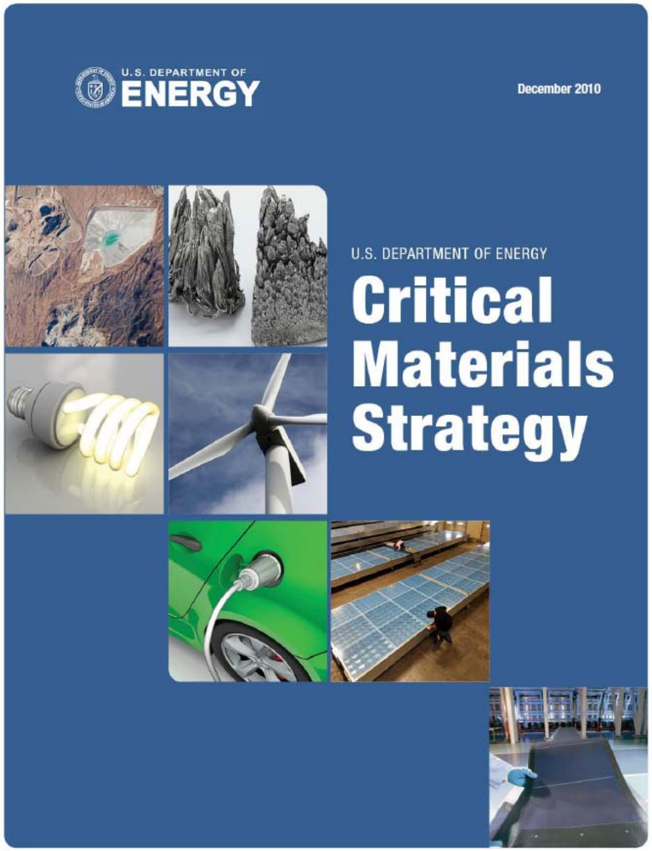
US DOE: Critical Materials Strategy (Dec 2010)

Coordinated Critical Materials Effort

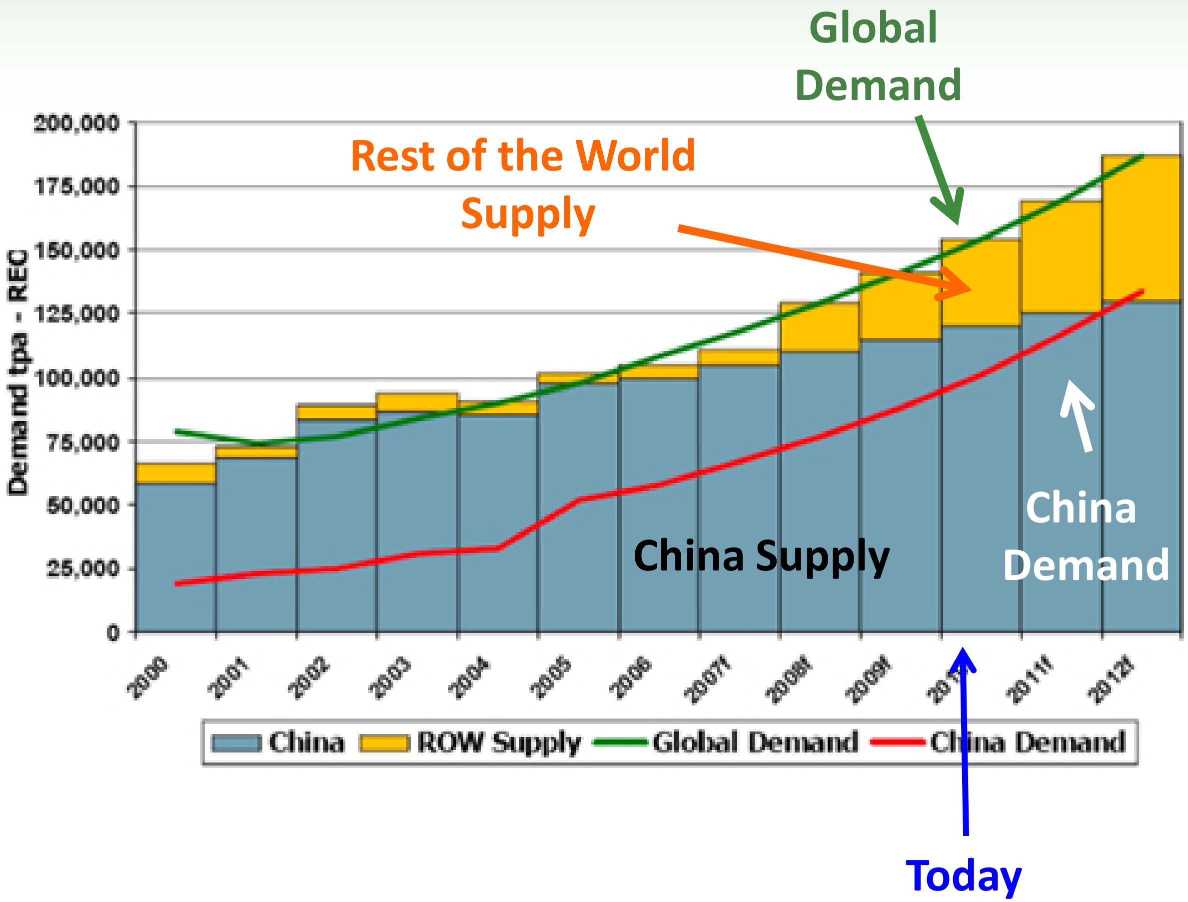
- Policy and International Affairs (PI) led Department-wide Critical Materials Strategy Study

  [David Sandalow, Assistant Secretary, PI]

- US-Japan Roundtable (LLNL) on Rare Earths (Nov 2010)
- US-EU Workshop on Rare Earths Research (Dec 2010)
- ARPA-E Workshop on Critical Materials Technology (Dec 2010)



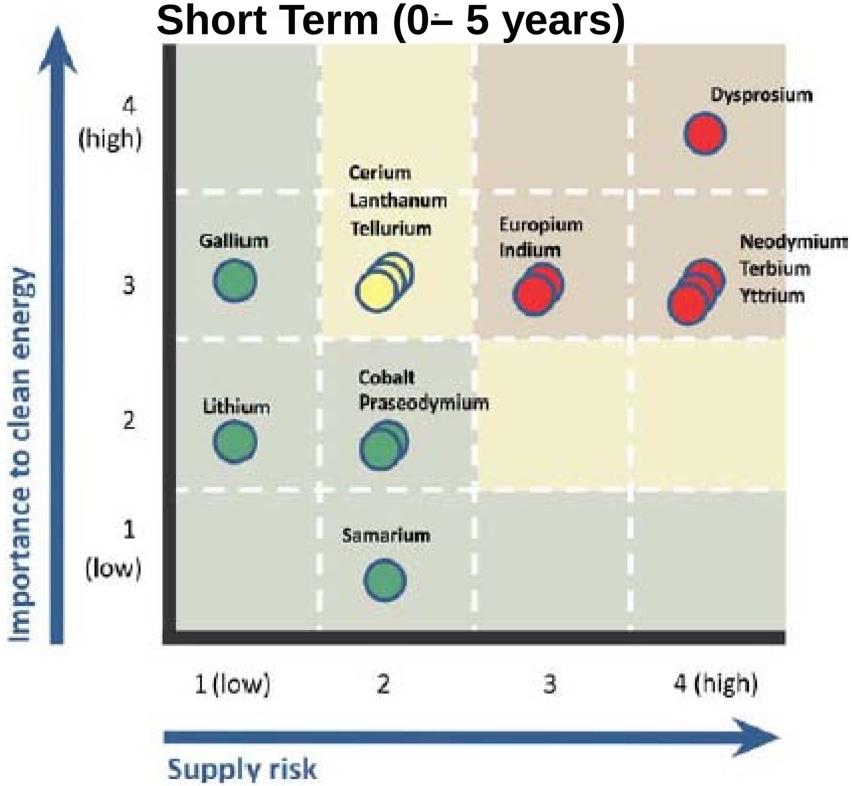
Shifting Economics Of Rare Earth Materials



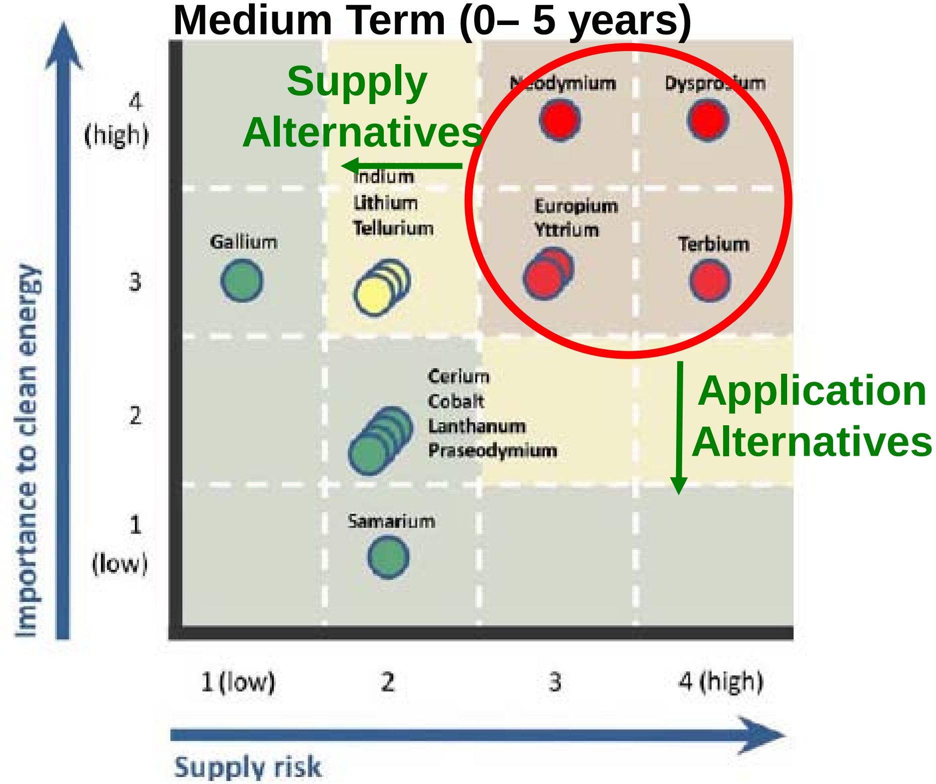
Within 5 Years: World's Dominant Supplier of Rare Earth Materials May Switch From a Net Exporter to a Net Importer

Rare Earth Criticality by Element

Short Term (0– 5 years)

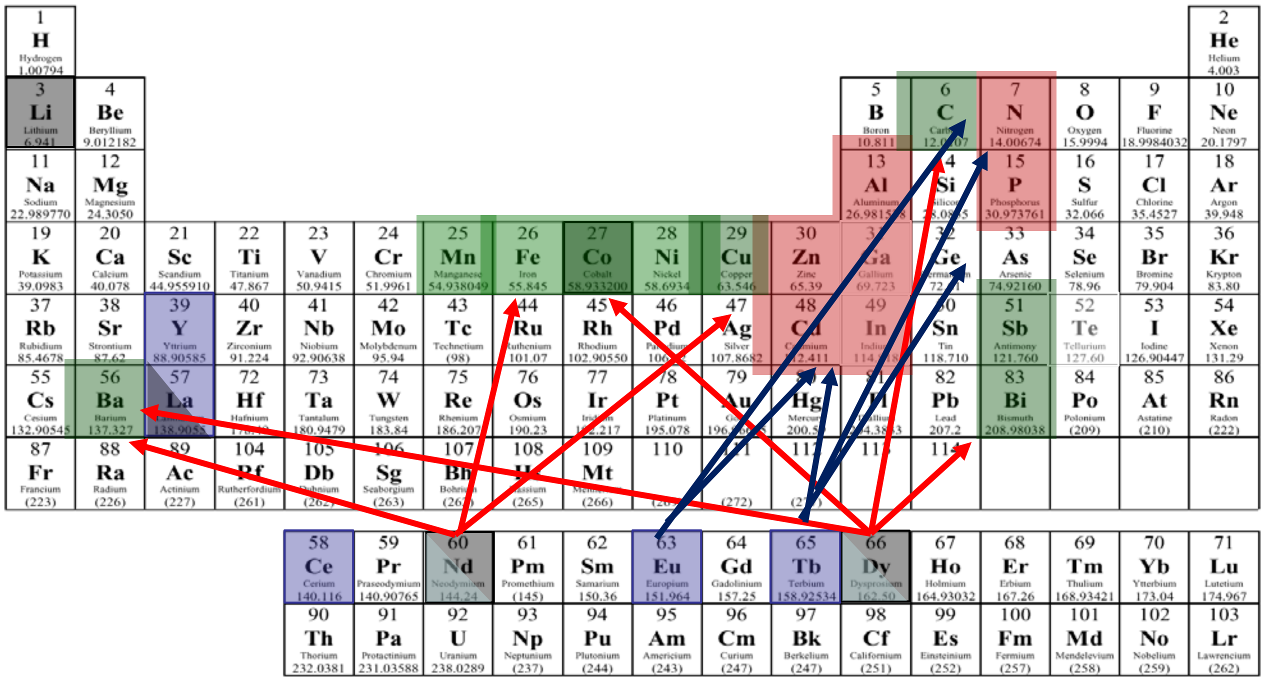


Medium Term (0– 5 years)



US DOE: Critical Materials Strategy (Dec 2010)

Possible Approach: Eliminate Need for Material



U.S. DEPARTMENT OF ENERGY

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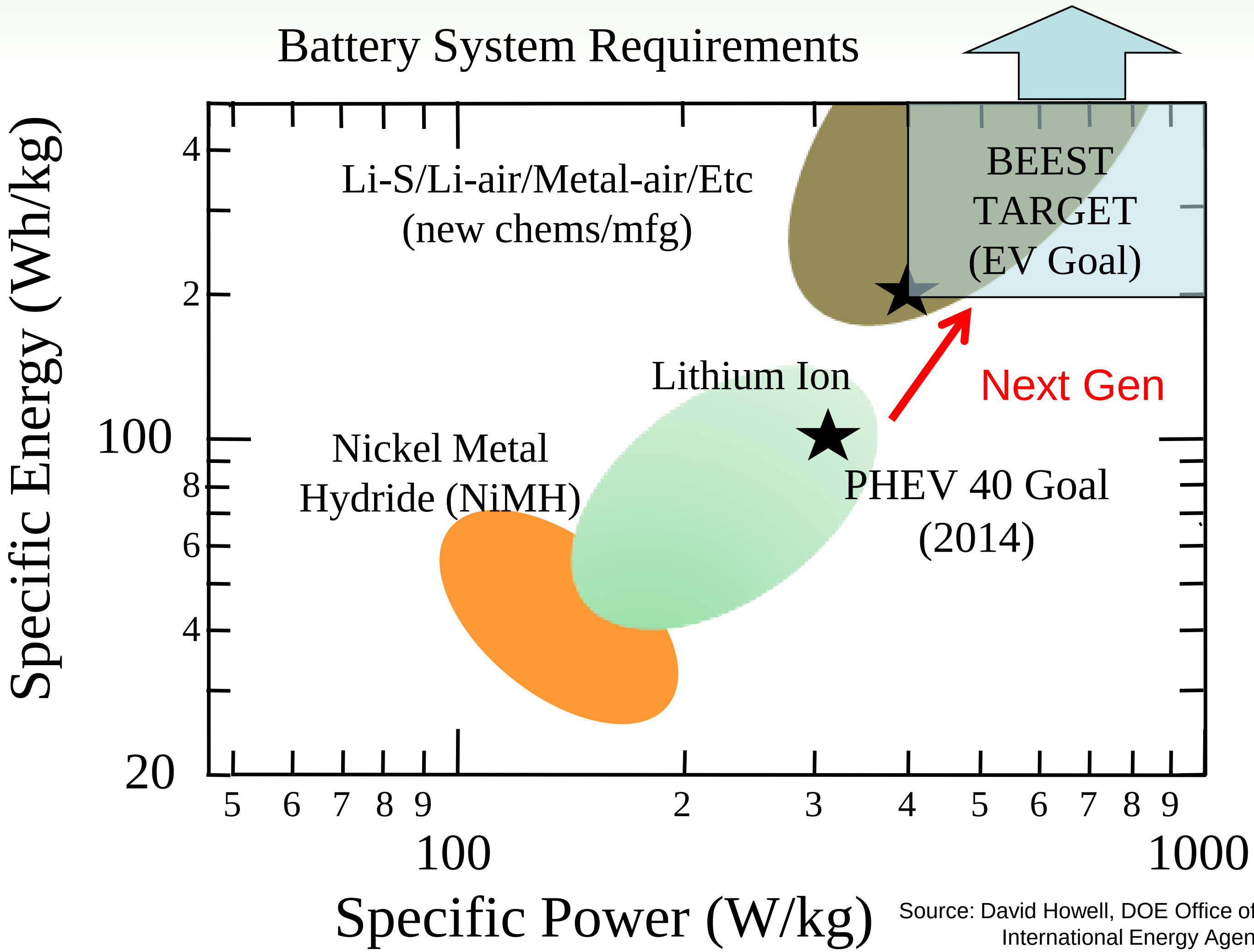
Batteries for Electrical Energy Storage in Transportation (BEEST) Program



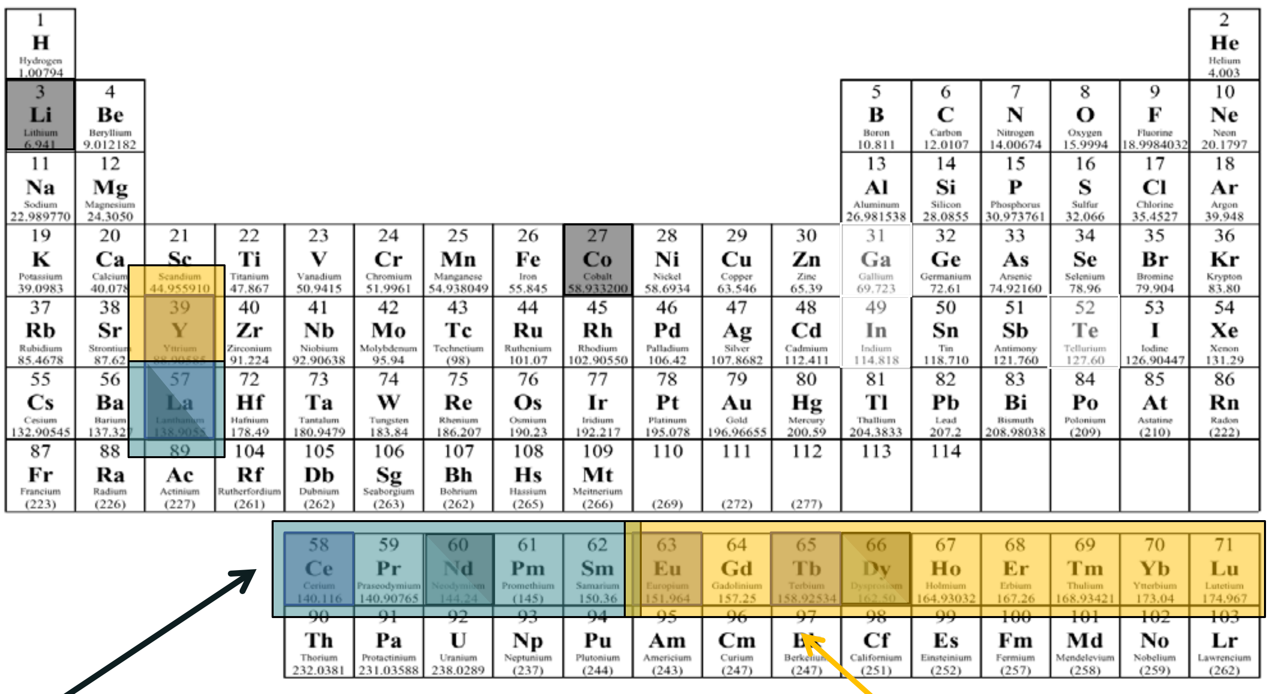
Storage Cost

Current Target: $1,000/kWh

BEEST Target: $250/kWh

Source: David Howell, DOE Office of Vehicle Technologies, 2009. International Energy Agency, *Technology Roadmaps: Electric and Plug-in Hybrid Electric Vehicles*

Possible Approach: Get Most From Available Supply

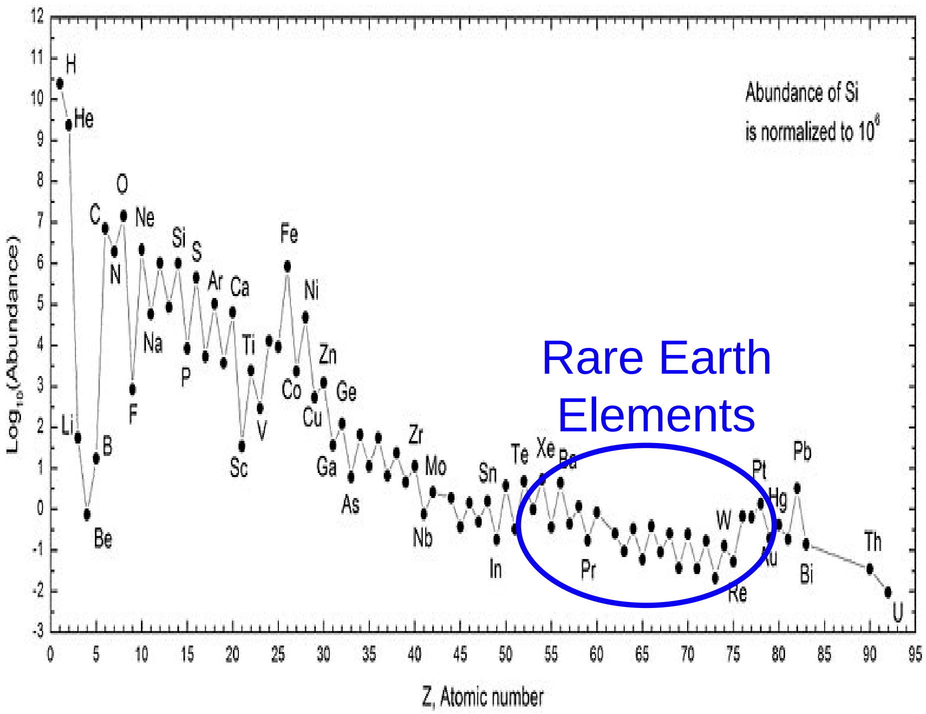


Light Rare Earth Elements

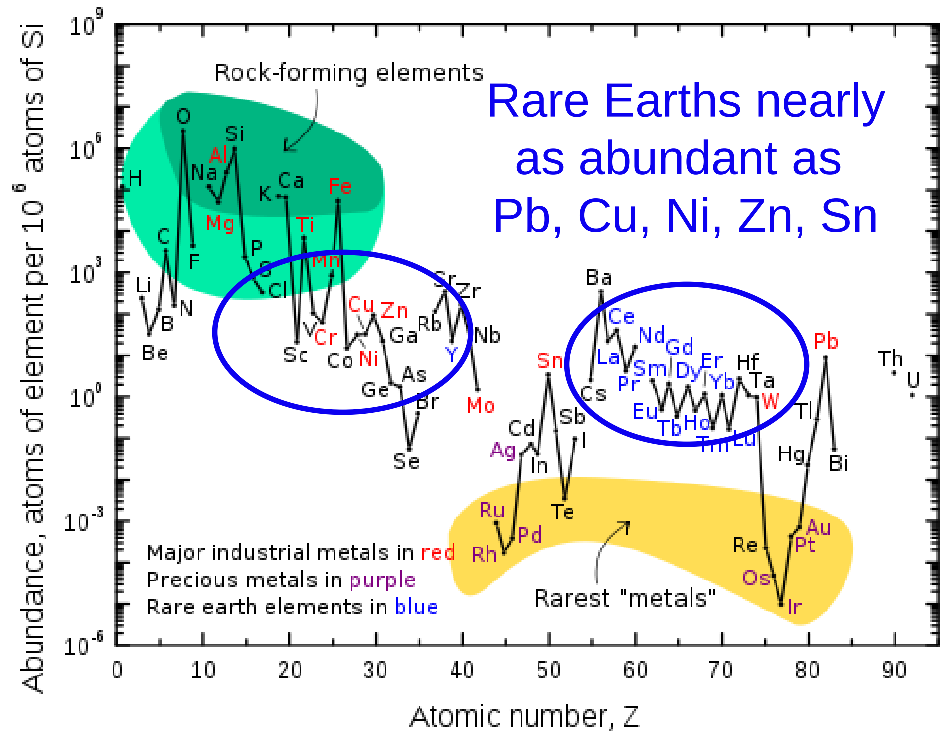
Heavy Rare Earth Elements

Rare Earth Elements Are Not That Rare

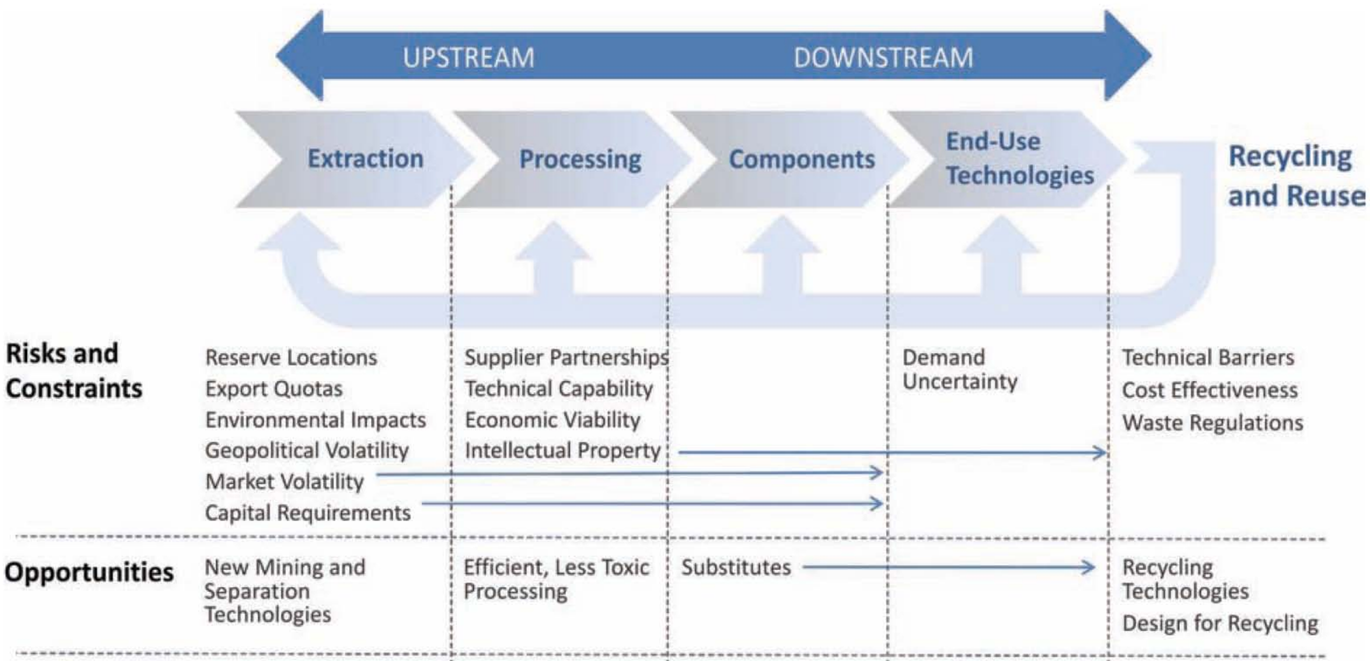
Solar System Abundance

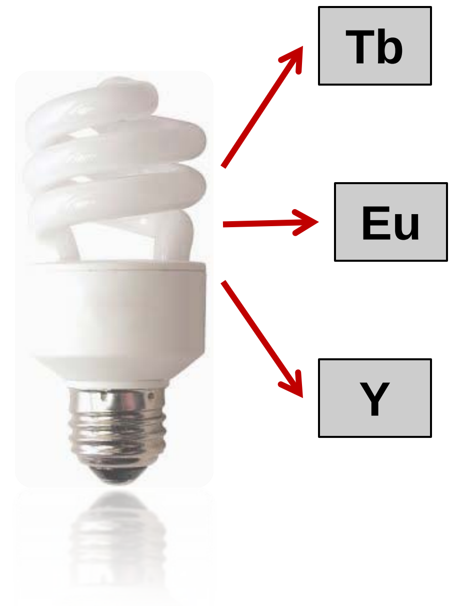


Upper Crust Abundance

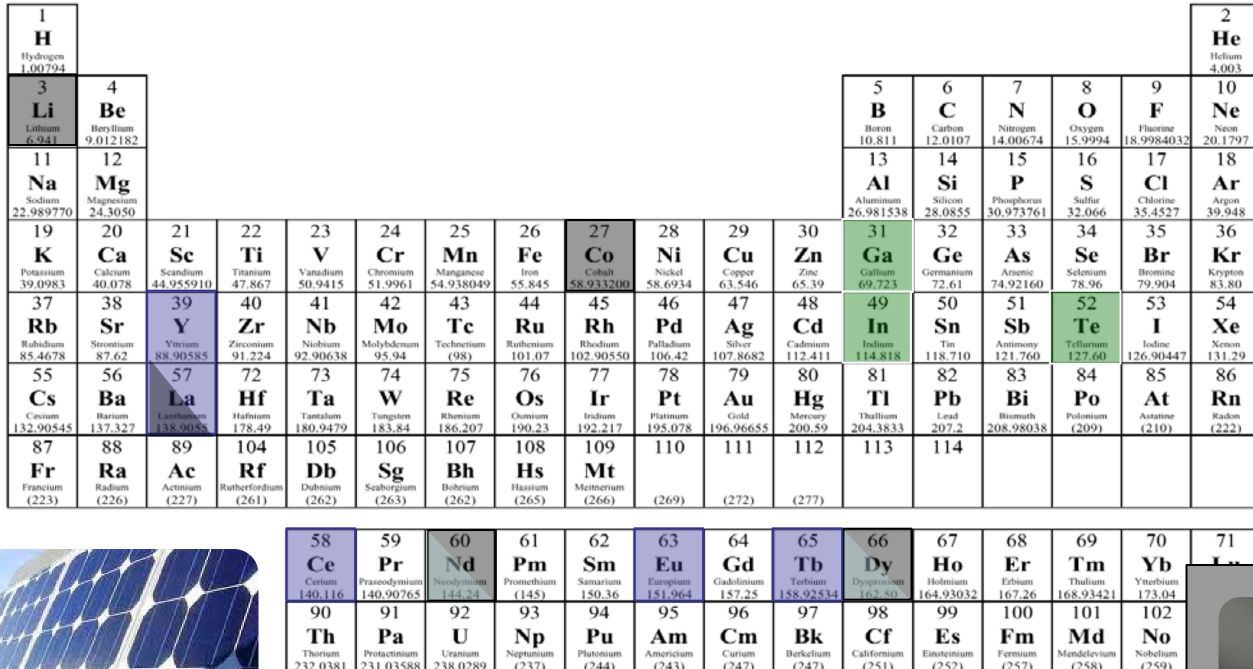


Developing Technology Alternatives Across Supply Chain





Critical Materials in Clean Energy from DOE-Wide Study



Vehicles

Lighting

Solar PV

Wind

Key Elements in Energy-Wide Supply Chain

Traditional Energy

Smart Grid

Vehicles

Lighting

Solar PV

Wind

Technology Opportunity Areas for Study

Vehicles

Lighting

Solar PV

Wind

Traditional Energy

Smart Grid

Batteries

Phosphors

Transparent Contacts

Permanent Magnets

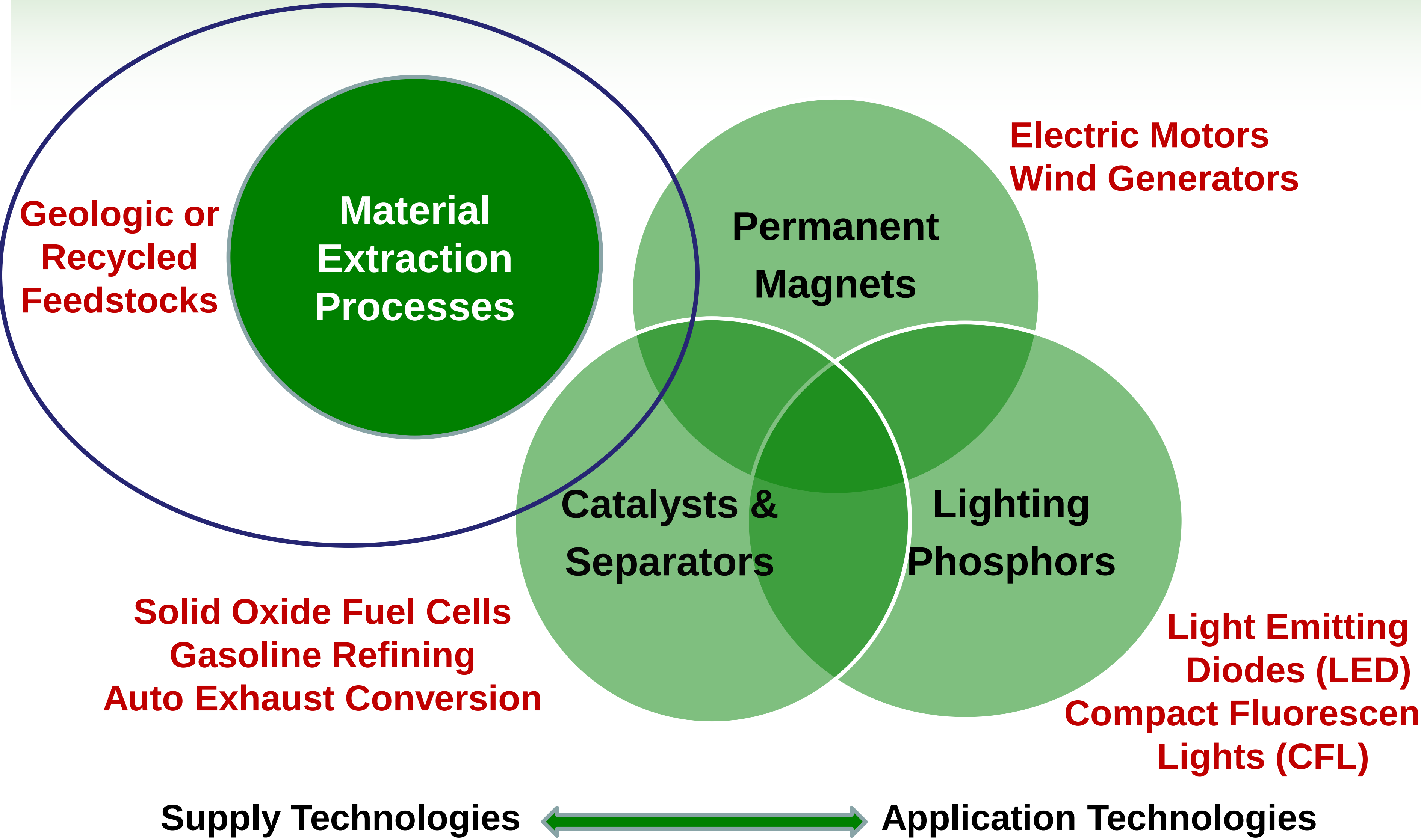
Oxygen Separators

Catalysts

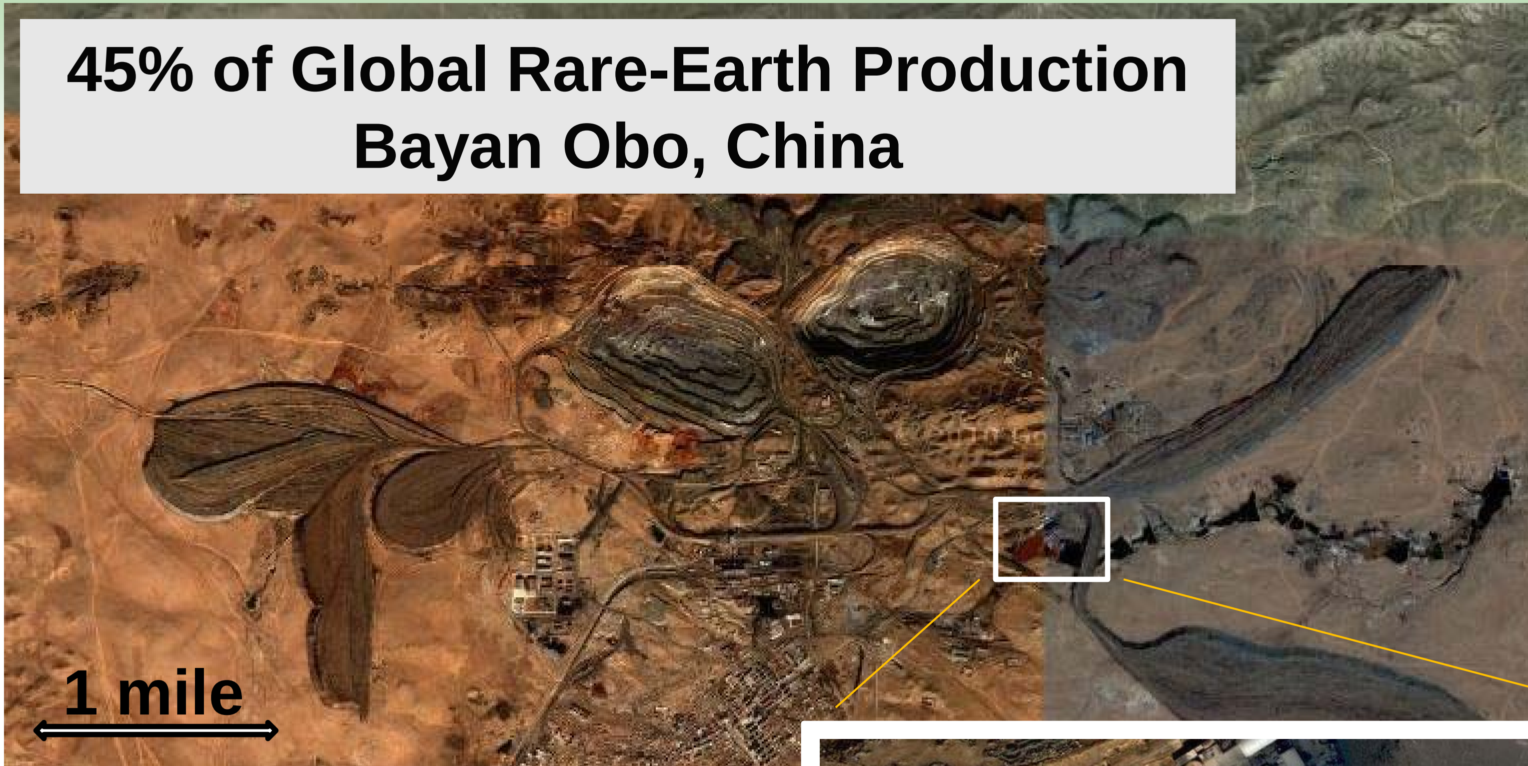
Opportunities For New, Disruptive Approaches to Technology Needs

Metrics to Drive New Learning Curves and Approaches

ARPA-E Workshop: Critical Materials Technology



45% of Global Rare-Earth Production
Bayan Obo, China

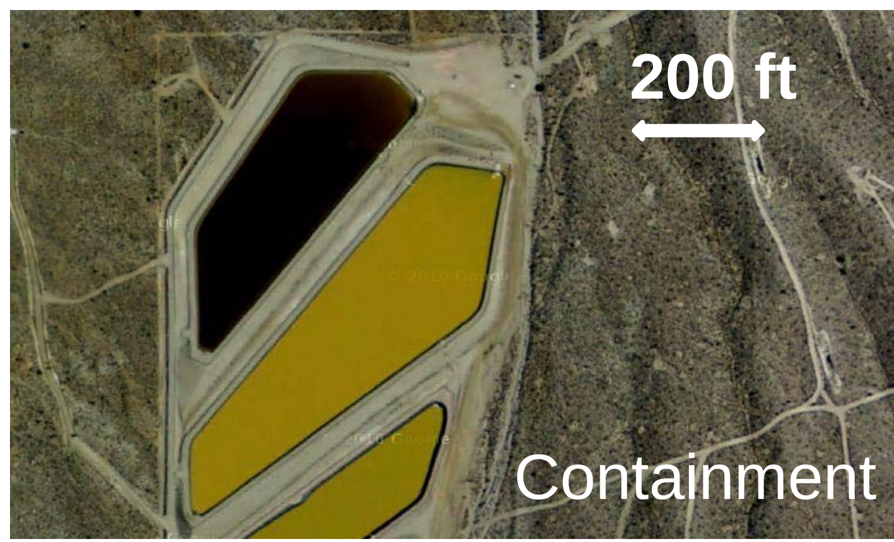


<u>Primary Ore</u>:
Bastnasite: RE-$(CO_3)F$
800 million metric tons; 6% REO

<u>Secondary Ore</u>:
Monazite: RE-PO_4

Photos: Google Maps

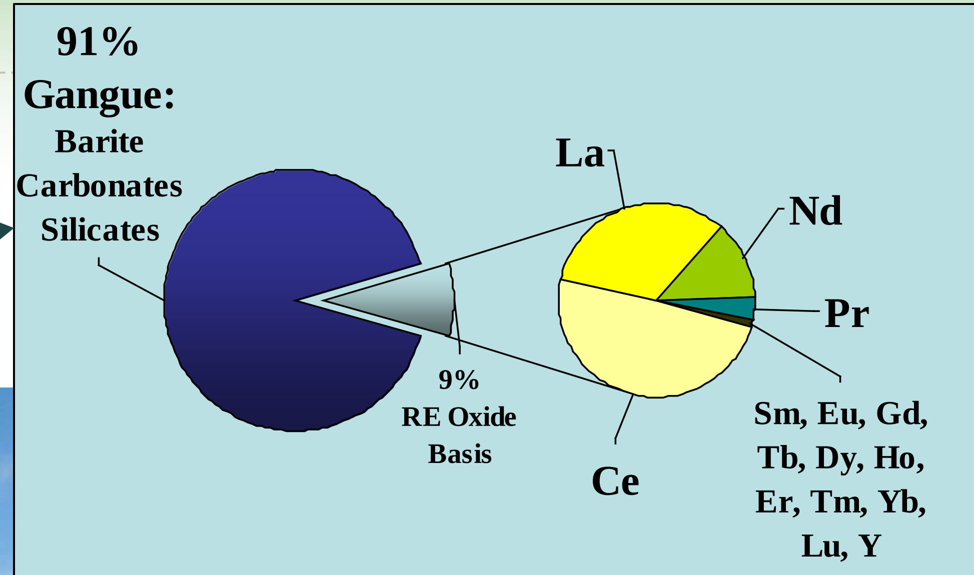
US Rare-Earth Production Capability
Mountain Pass, CA (re-opened by Molycorp)



<u>Primary Ore</u>:
Bastnasite: RE-(CO_3)F
3.3 million metric tons:
7-9% REO

Photos: Google Maps

Molycorp Rare Earth Facility
Mountain Pass, CA



Different Types of Rare Earths

Heavy and Light Rare Earths are from different Ores

<u>Light Rare Earths</u>

Neodymium – Magnets

<u>Heavy Rare Earths</u>

Dysprosium - High Temp Magnets

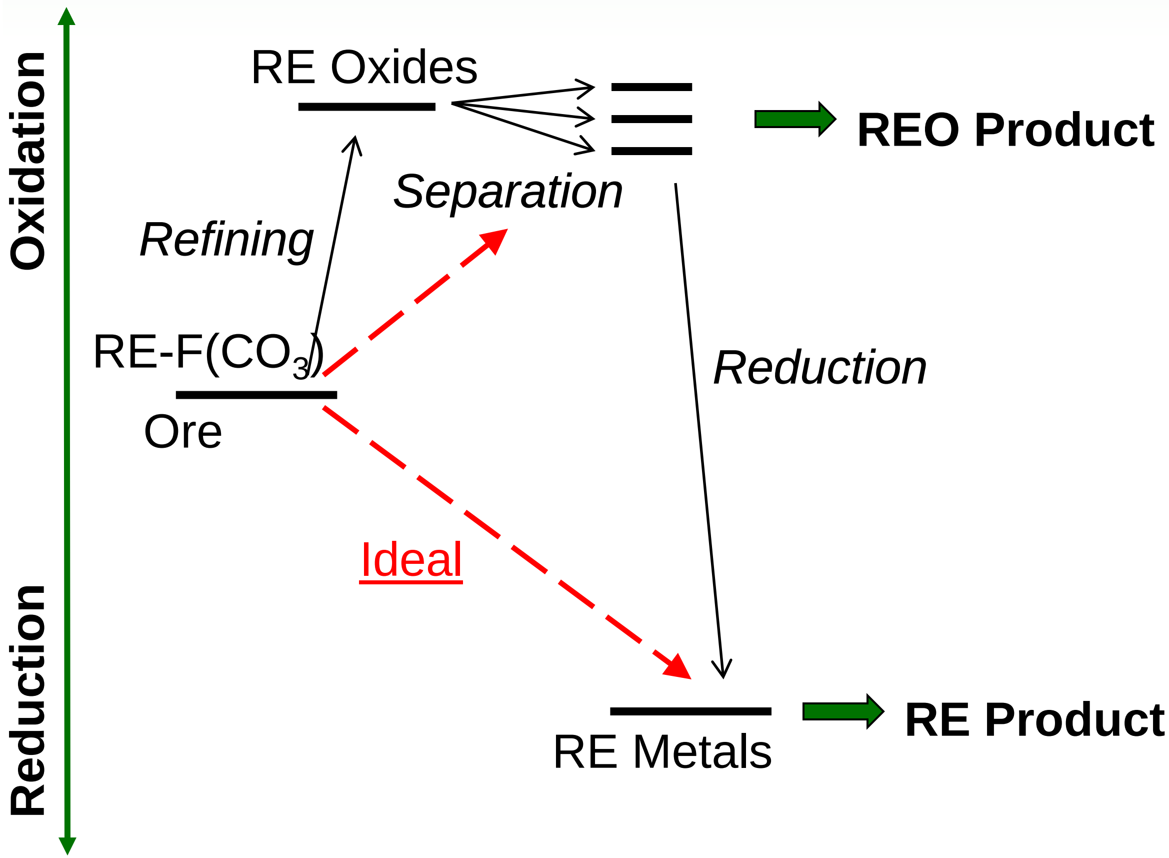
Yttrium – SOFCs and Phosphors

Terbium – Phosphors

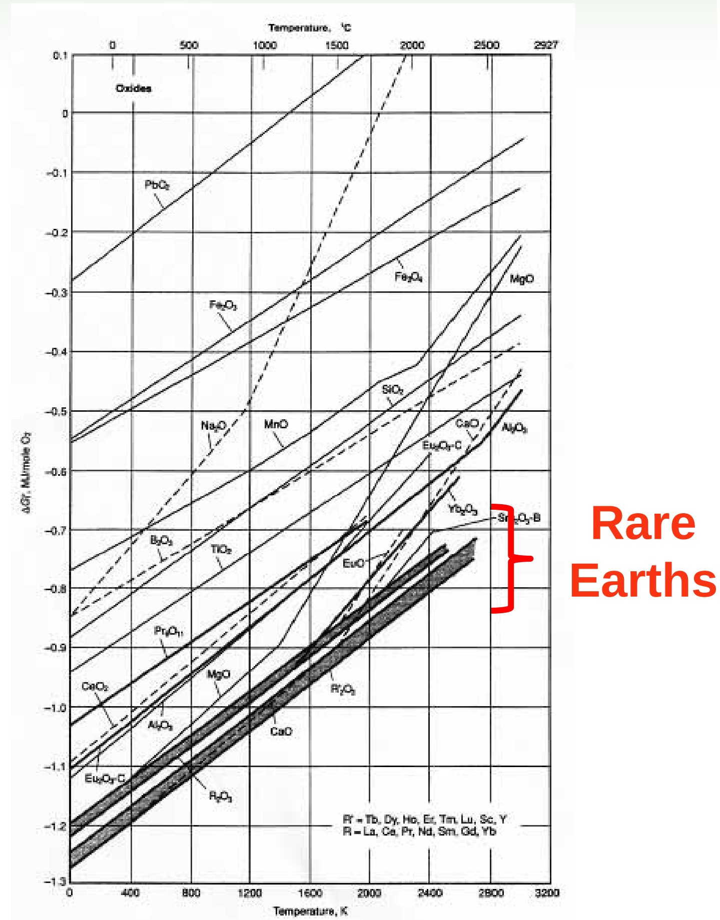
Europium - Phosphors

		LIGHT				MEDIUM			HEAVY									
TYPE	LOCATION (S)	Lanthanum (La)	Cerium (Ce)	Praseodymium (Pr)	Neodymium (Nd)	Samarium (Sm)	Europium (Eu)	Gadolinium (Gd)	Terbium (Tb)	Dysprosium (Dy)	Holmium (Ho)	Erbium (Er)	Thulium (Tm)	Ytterbium (Yb)	Lutetium(Lu)	Yttrium(Y)
Currently active:																		
Bastnäsite	Bayan Obo, Inner Mongolia	23.0	50.0	6.2	18.5	0.8	0.2	0.7	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Xenotime	Lahat, Perak, Malaysia	1.2	3.1	0.5	1.6	1.1	0.0	3.5	0.9	8.3	2.0	6.4	1.1	6.8	1.0	61.0
Rare earth laterite	Xunwu, Jiangxi Province, China	43.4	2.4	9.0	31.7	3.9	0.5	3.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	8.0
Ion adsorption clays	Longnan, Jiangxi Province, China	1.8	0.4	0.7	3.0	2.8	0.1	6.9	1.3	6.7	1.6	4.9	0.7	2.5	0.4	65.0
Loparite	Lovozerskaya, Russia	28	57.5	3.8	8.8	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Various	India	23	46	5	20	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Various	Brazil	N.A.														
Possible to come online in the next 5 years:																		
Bastnäsite [22]	Mountain Pass, California, United States	33.2	49.1	4.3	12.0	0.8	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Monazite	Mount Weld, Australia	26.0	51.0	4.0	15.0	1.8	0.4	1.0	0.1	0.2	0.1	0.2	0.0	0.1	0.0	0.0
	Eastern coast [23], Brazil	24.0	47.0	4.5	18.5	3.0	0.1	1.0	0.1	0.4	0.0	0.1	0.0	0.0	0.0	1.4
Apatite	Nolans bore, Australia	20.0	48.2	5.9	21.5	2.4	0.4	1.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Fergusonite [24]	Nechalaco, Canada	16.9	41.4	4.8	18.7	3.5	0.4	2.9	1.8	0.7	0.0	0.0	0.0	0.0	0.0	7.4
Bastnäsite & Parisite	Dong Pao, Vietnam	32.4	50.4	4.0	10.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007
Alanite & apatite	Hoidas Lake, Canada	19.8	45.6	5.8	21.9	2.9	0.6	1.3	0.1	0.4	0.0	0.0	0.0	0.0	0.0	1.3
Trachyte	Dubbo Zirconia, Australia	19.5	36.7	4.0	14.1	2.5	0.1	2.1	0.3	2.0	0.0	0.0	0.0	0.0	0.0	15.8

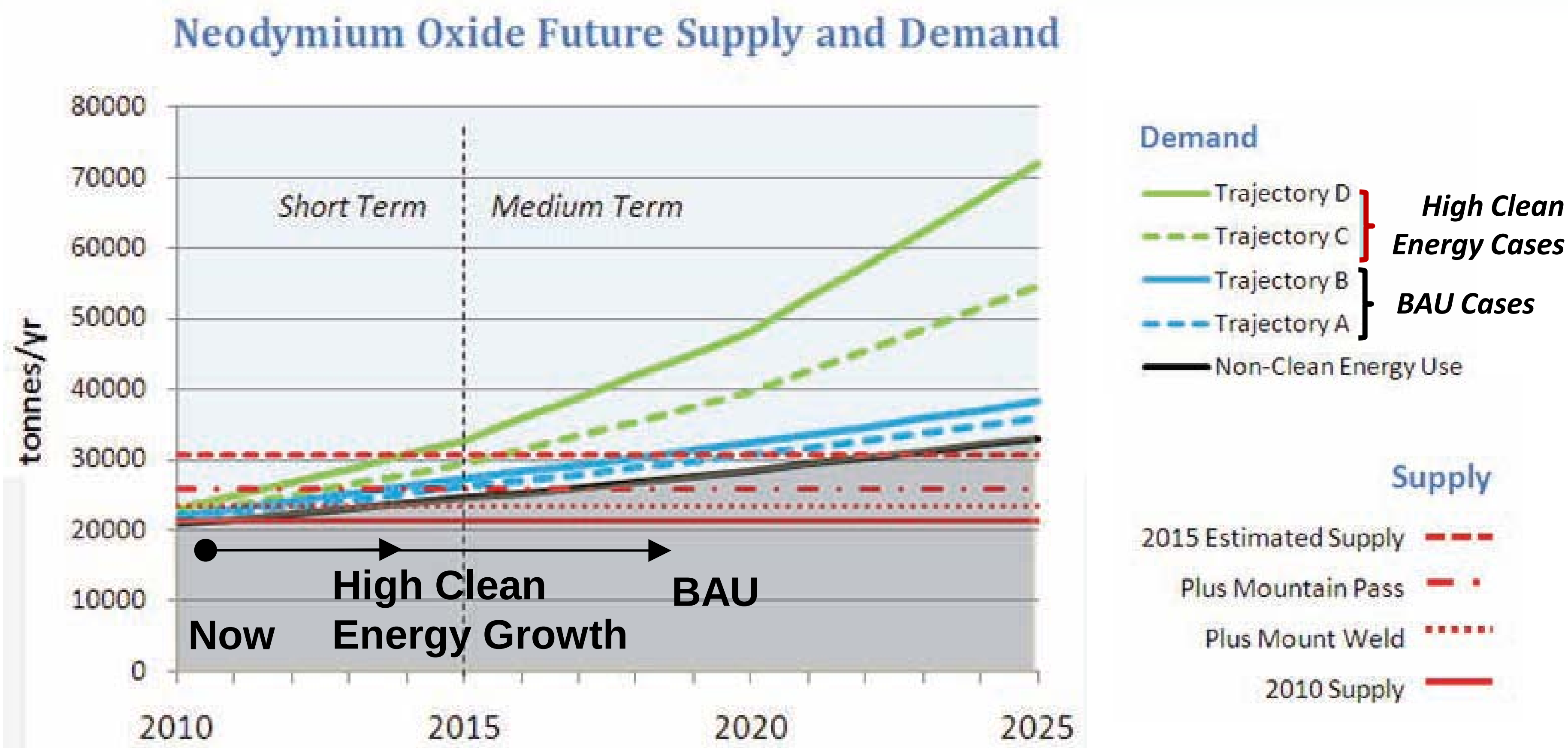
Rare Earth Oxide and Metal Extraction Process



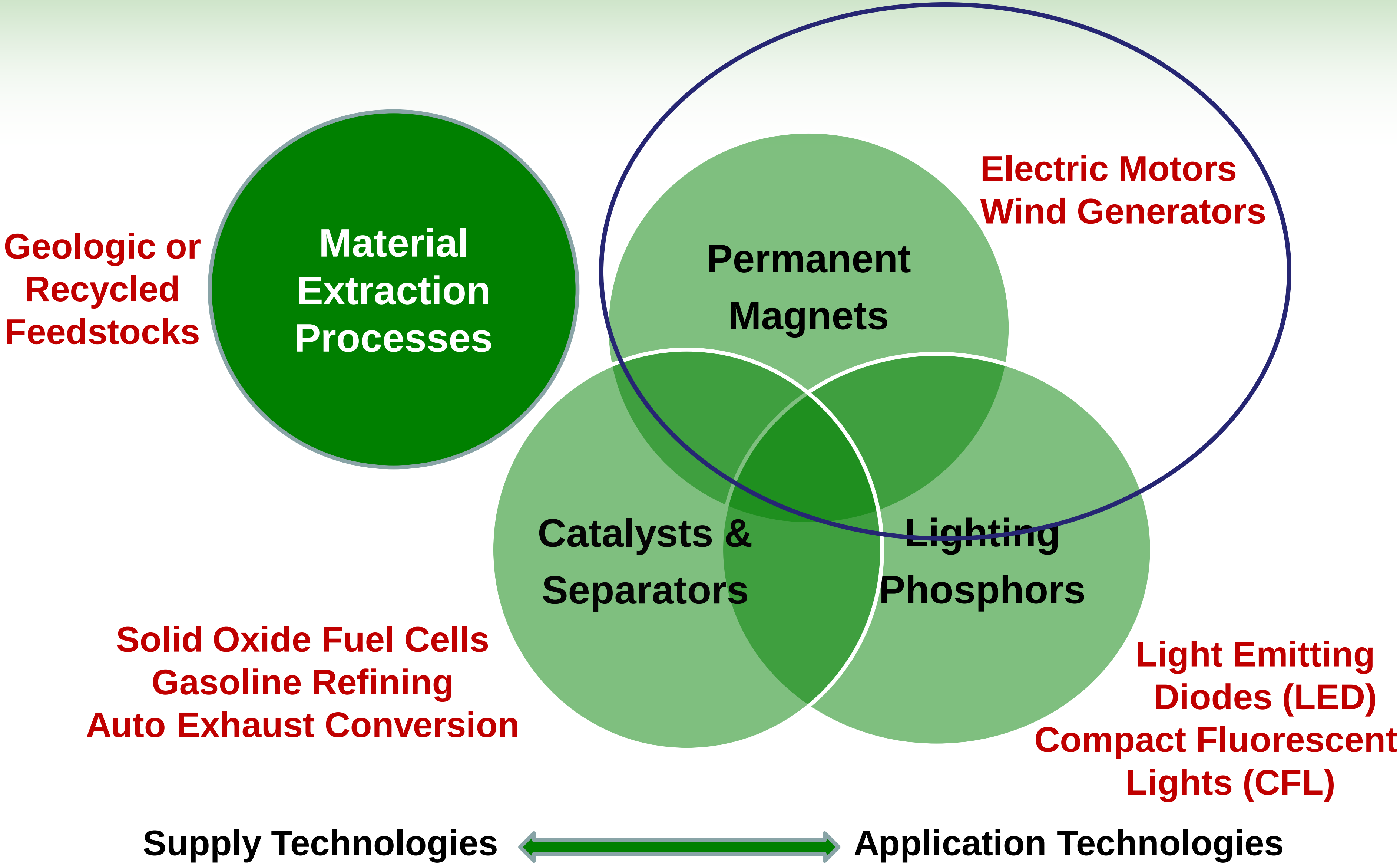
Rare-Earth Processing Cycle



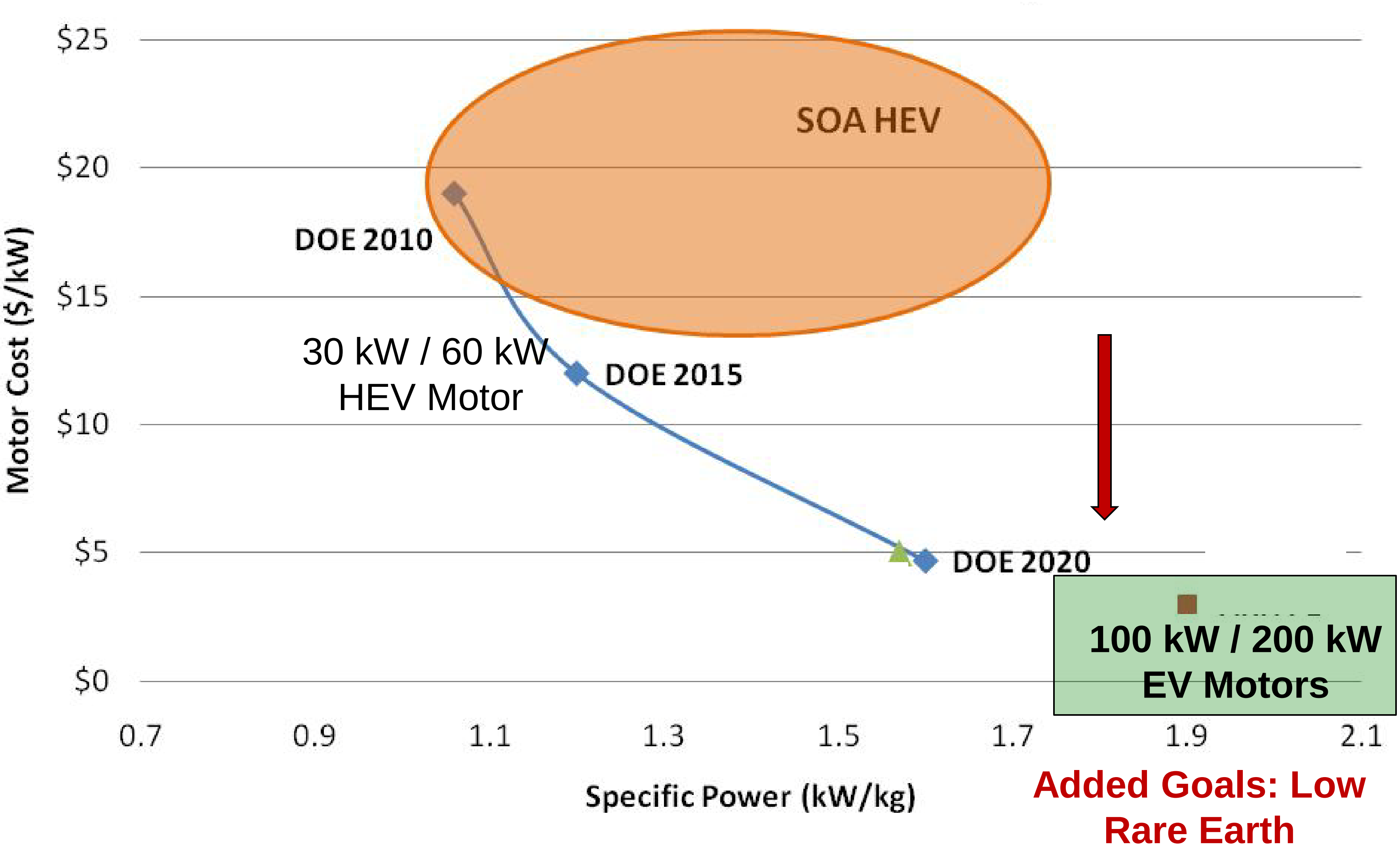
Supply and Demand Scenarios Neodymium (Permanent Magnets)



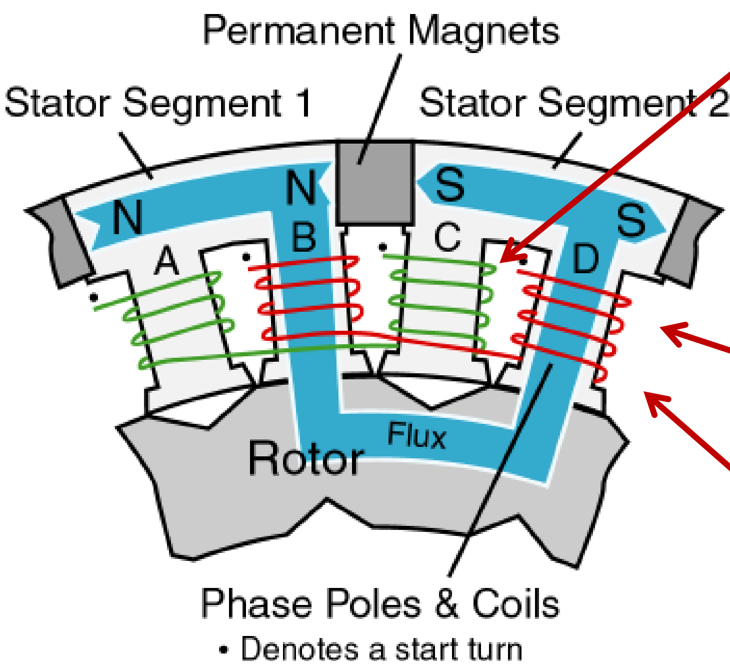
ARPA-E Workshop: Critical Materials Technology



Magnetic Systems: Motors for Electric Vehicle (EV) 2020 Roadmap Goals with Low Rare Earth Content



Advanced Electric Motor Concepts



High Temperature and Voltage Insulators for Windings

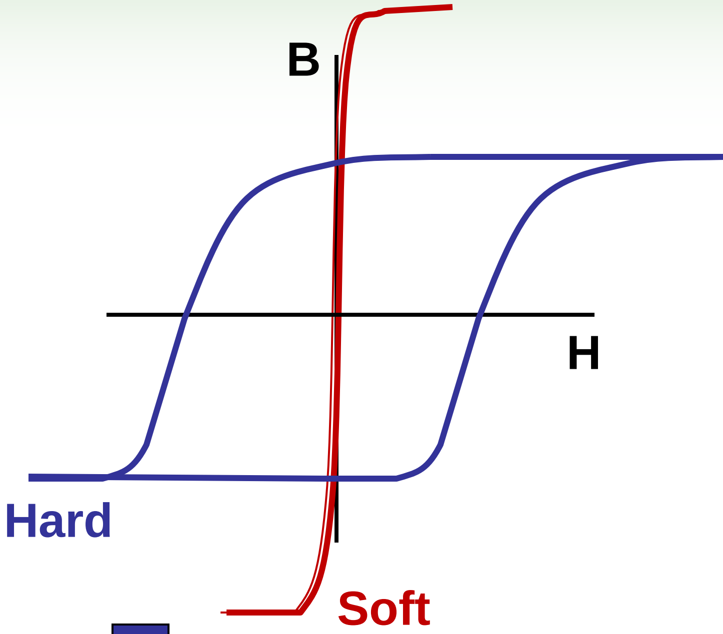
Non-Rare Earth Hard Magnetic Material

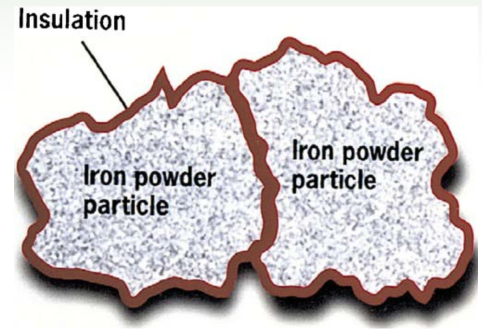
Complex Soft Magnetic Structures

Reluctance Path Switching

Example: Parallel Path Magnetic Motor Technology

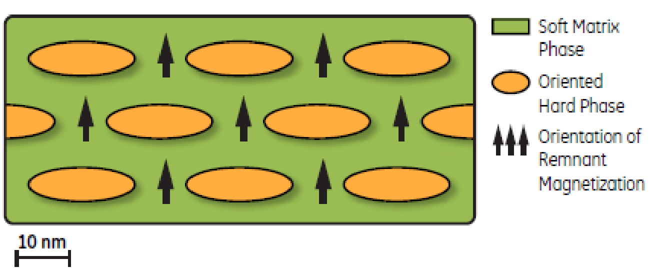
Needed Enabling Magnetic Materials





Soft Magnetic Nanocomposite

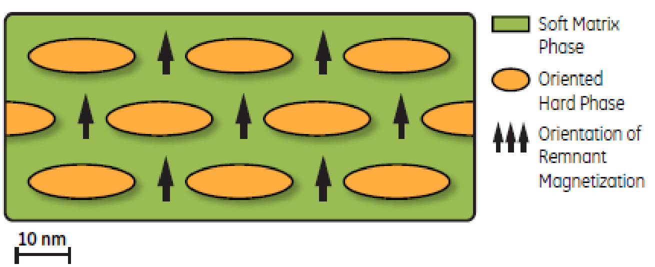
High Permeability (Fe, Fe-Si, Fe-Co)
Low Eddy Current Loss
Isotropic Permeability (ideal)
Manufacture-able / Moldable
Enables Novel Structures



Hard Magnetic Nanocomposite

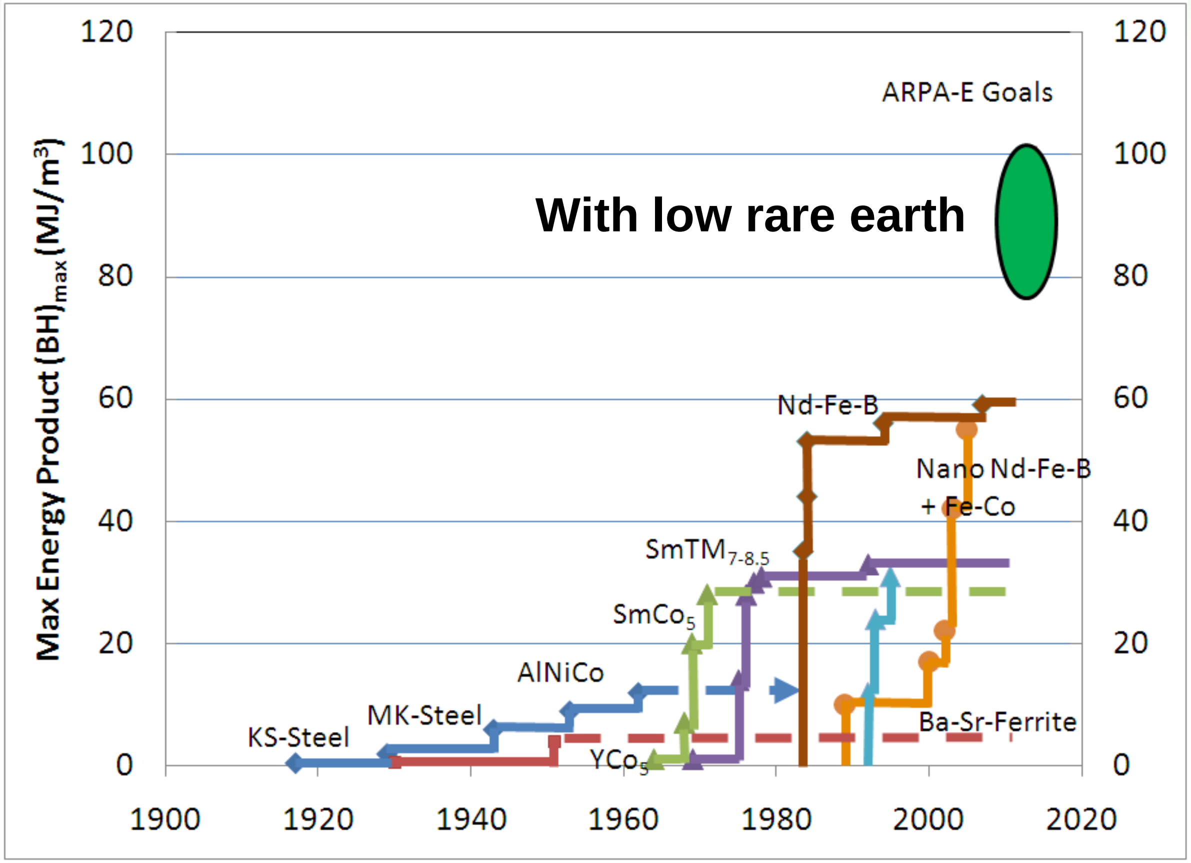
Spring Exchange Coupling
Coercivity of Hard Phase (SmCo, NdFeB)
Remnance of Soft Phase (Fe, Fe-Co)
High Energy Density
Reduced Rare Earth Content
Current: U Del. & GE

Nanocomposite Permanent Magnets



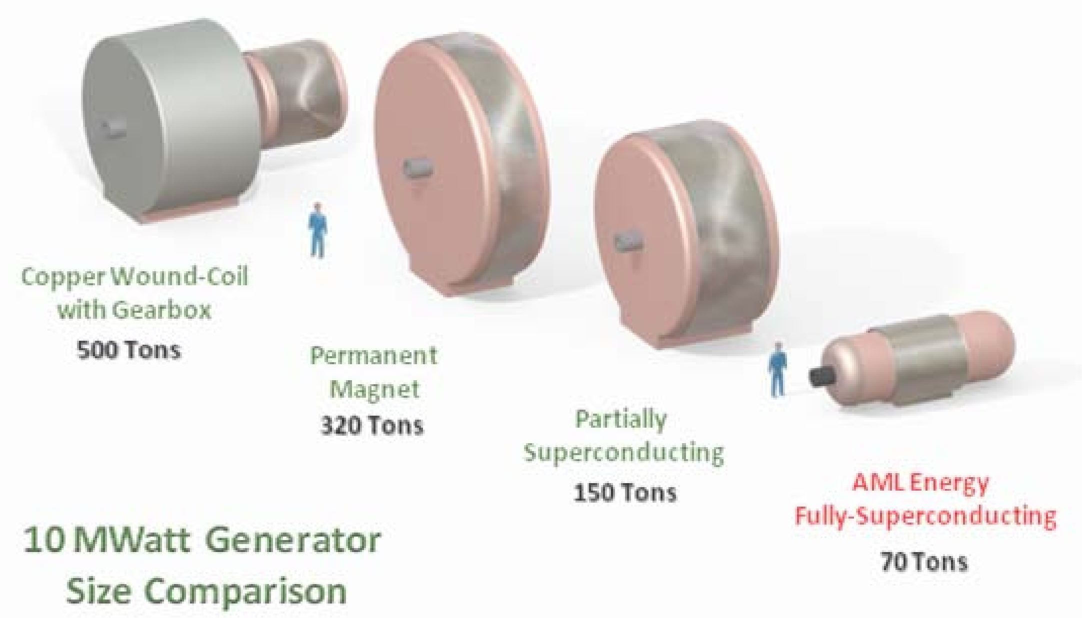
Core@Shell Hard/Soft Exchange Spring Coupled Nanocomposite Magnets with:

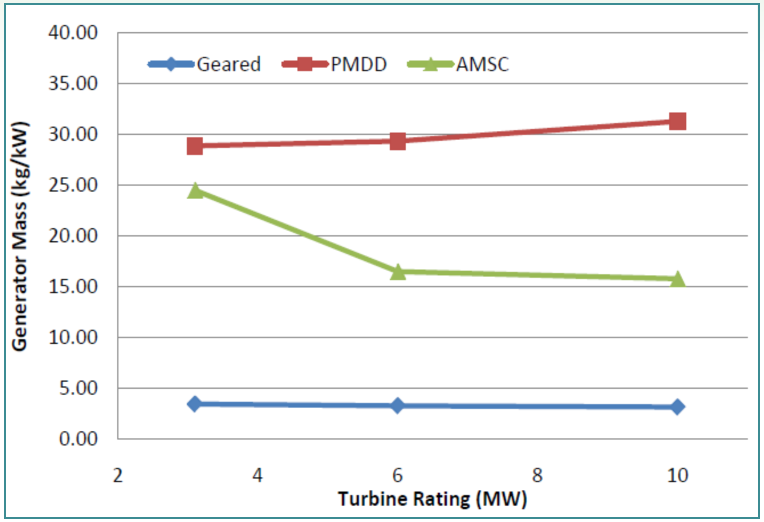
- 80 MGOe (vs 59 MGOe NdFeB)
- 59 MGOe with 80% less rare earth

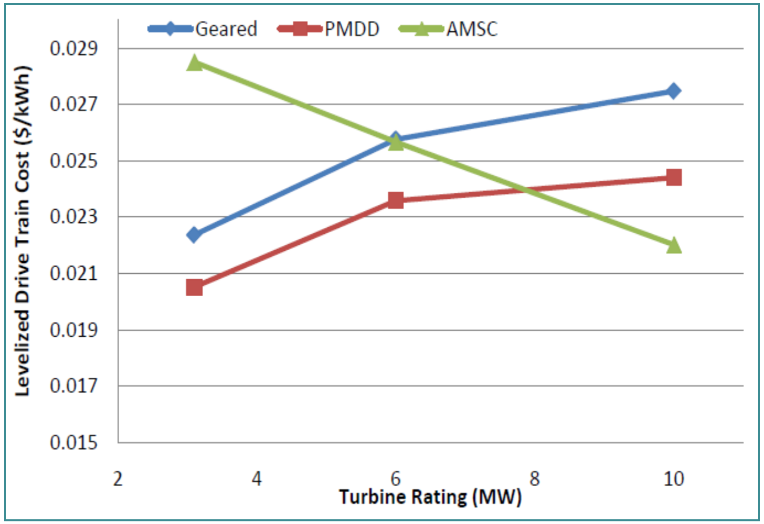


Nanocomposite exchange spring coupled permanent magnets with high energy product and less rare earths

Large Scale Wind Generator (>10MW) Systems







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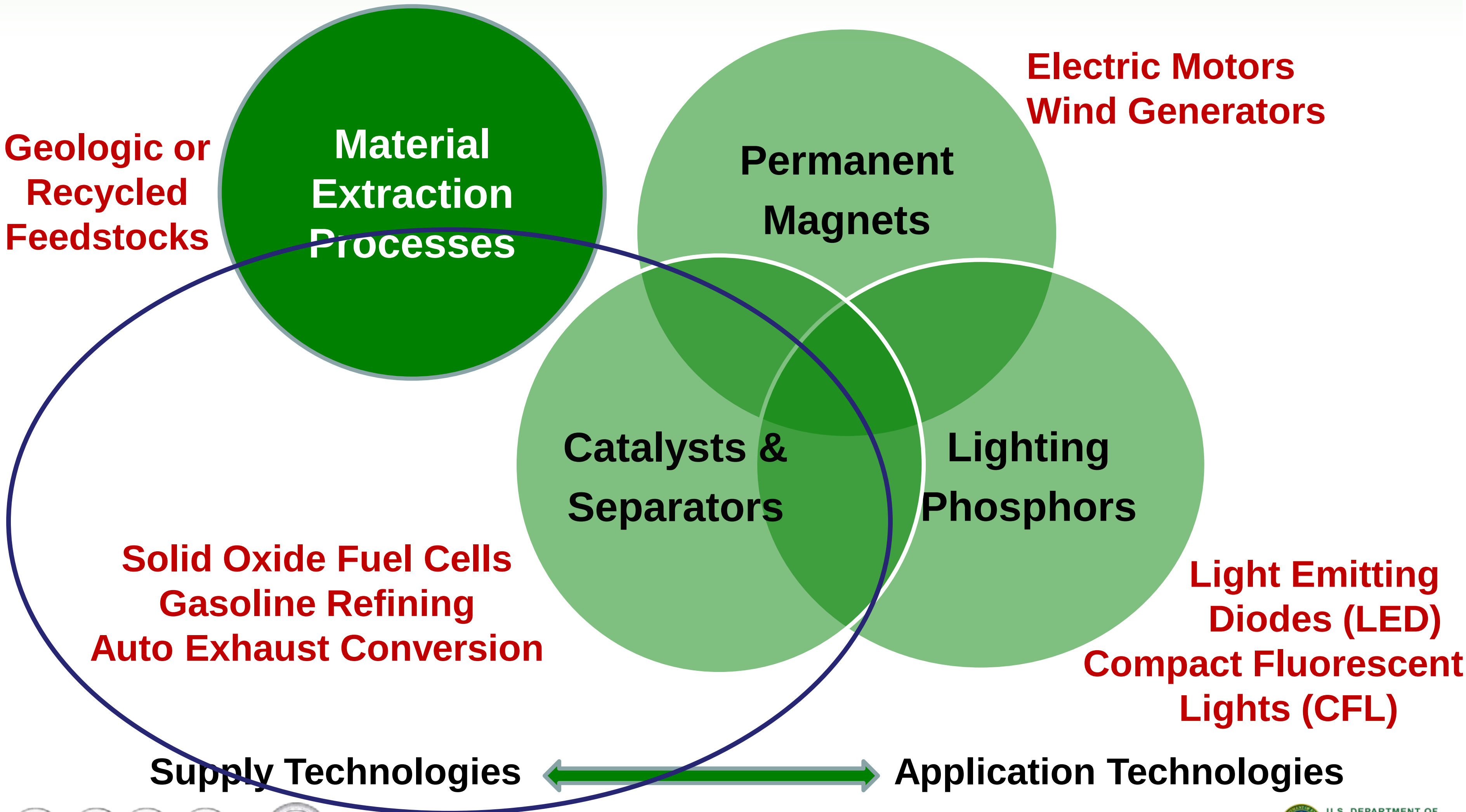
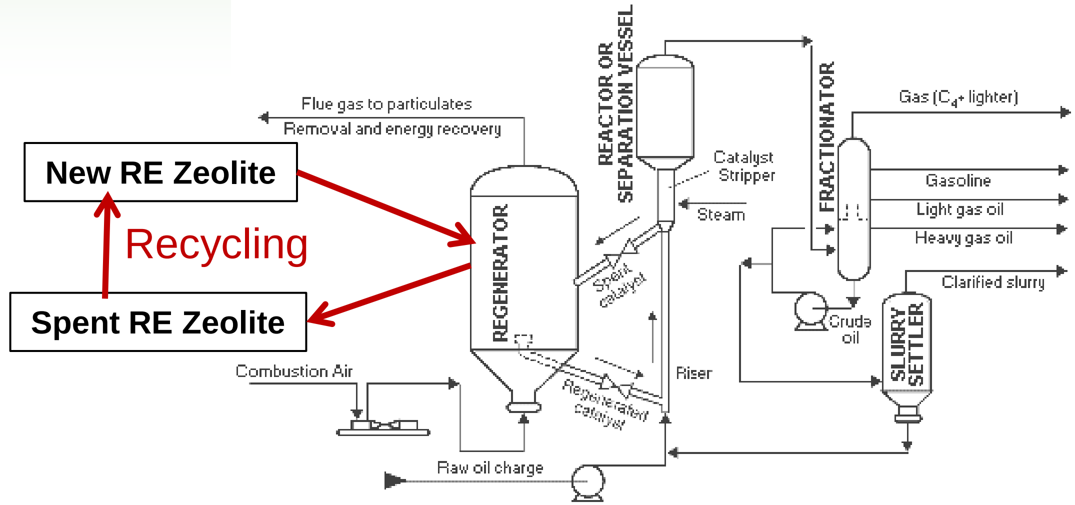


Catalysts: Fluid Catalytic Cracking



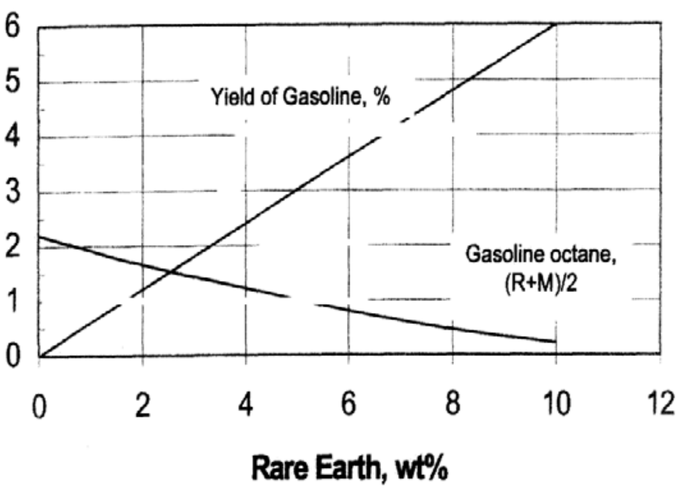
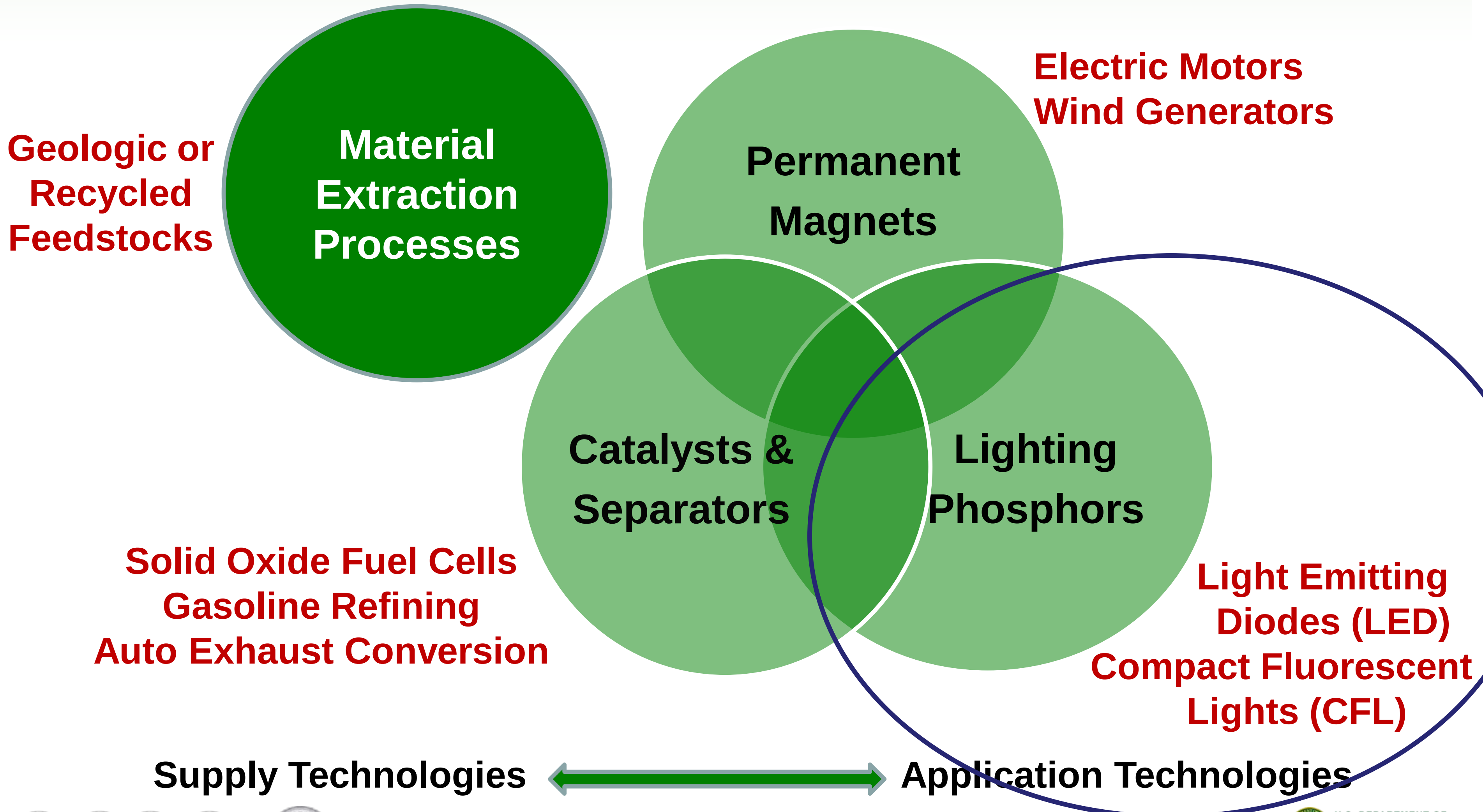


Figure 3-6. Effects of rare earth on gasoline octane and yield.

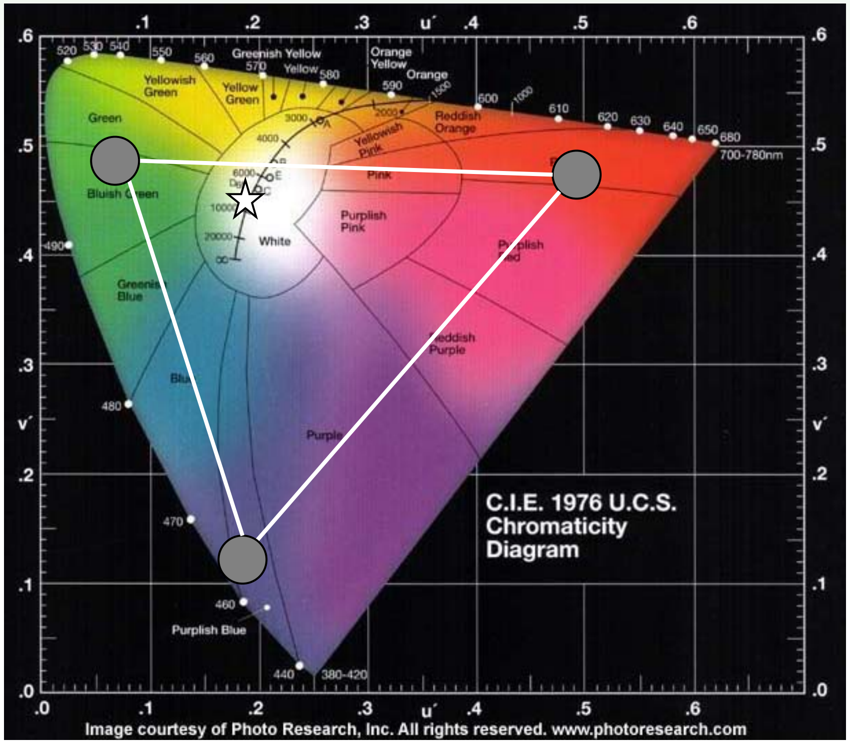
1-2% catalysts replaced per day.
All catalyst replaced every 2 months due to loss of aluminum.
Old catalyst is landfilled.

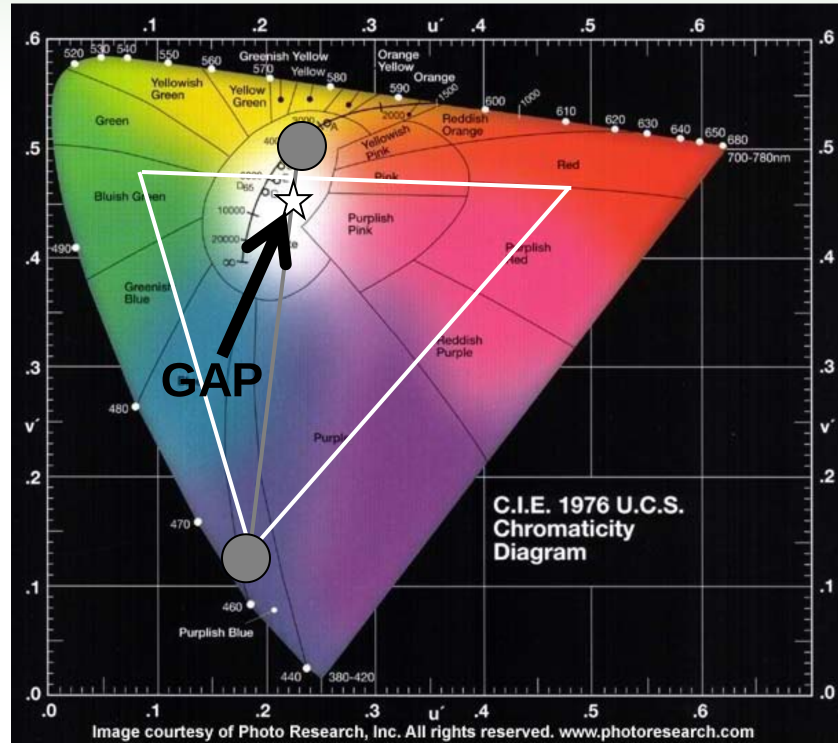
Recover Rare-earth content from spent FCC catalyst could potentially have Impact.

ARPA-E Workshop: Critical Materials Technology



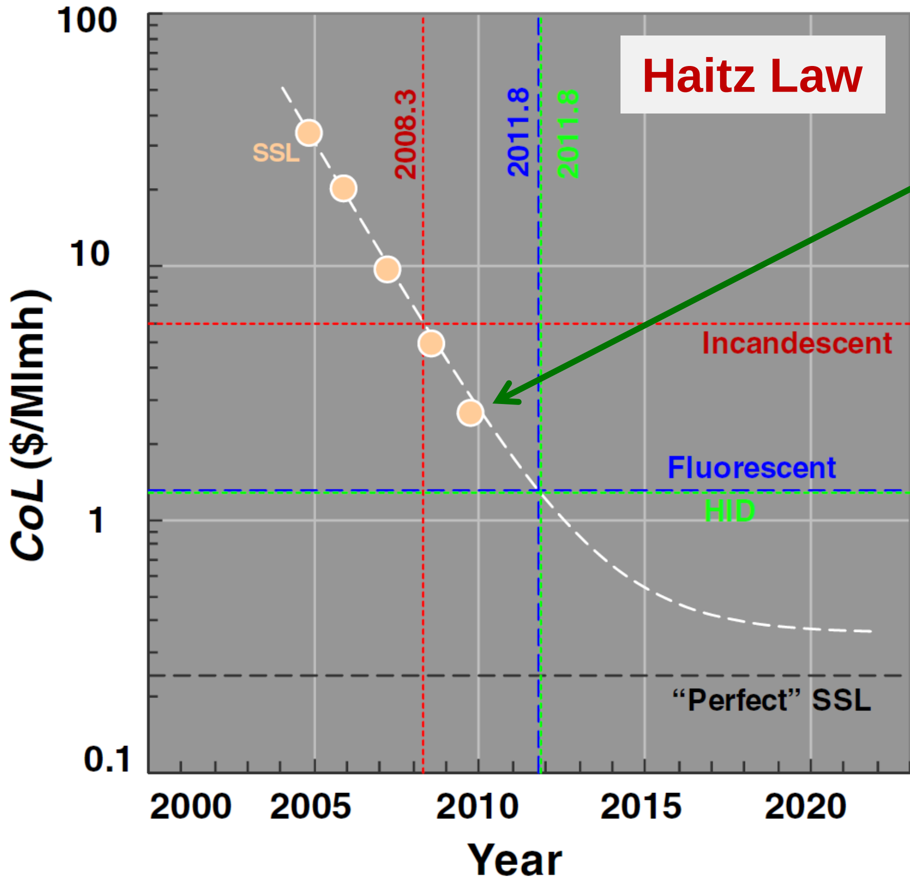
Application: Rare Earth Phosphors for CFLs





Phosphor	Code	Color	Emission Wavelength	Nature	Rare Earth(s)
$BaMgAl_{10}O_{19}:Eu^{2+}$	BAM	Blue	450 nm	Broad band	Eu
$LaPO_4:Ce^{3+}, Tb^{3+}$	LAP	Green	545 nm	Sharp line	La,Ce,Tb
$Y_2O_3:Eu^{3+}$	YEO	Red	610 nm	Sharp line	Y, Eu

Cost of Lighting (CoL) vs. First Lumen Cost (Bulb)



J.Tsao, et.al., *Proc. IEEE* (9/09)

First Purchase Cost (per bulb)

$50-$120	Solid State Bulb
$2.00	Compact Fluorescent
$0.30	Incandescent

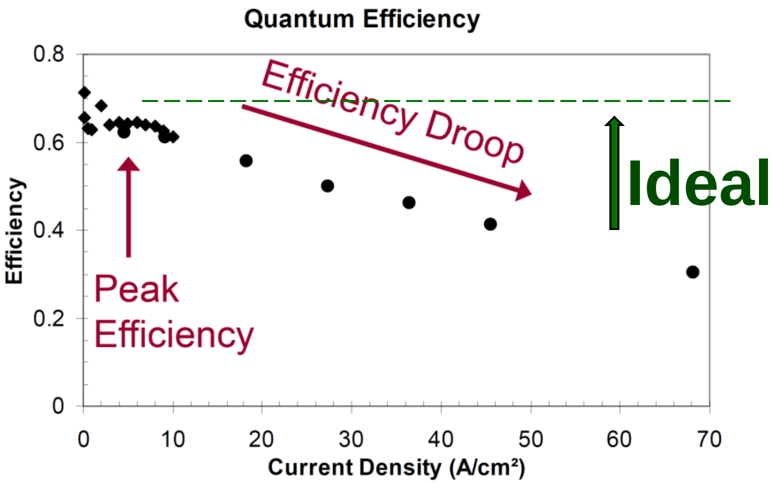
First Cost

Innovate Faster Than Global Competitors

(cost/klm)

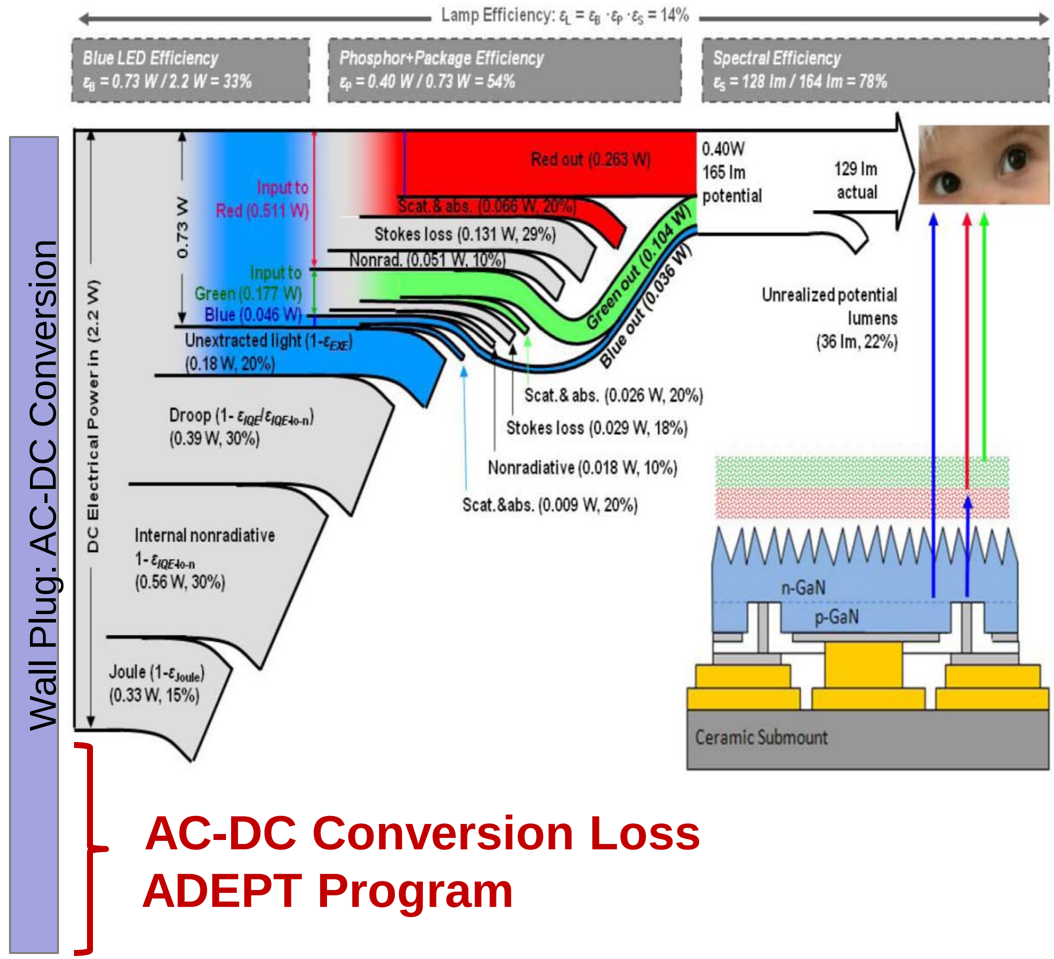
First Purchase Price for Lighting

Technical Pathway to Low First Cost LEDs: Eliminate Droop Losses Through Innovation



<u>Physical Origins of Droop</u>
Auger Recombination
Non-Radiative Defects
Carrier Overflow from MQWs
Crystal Polarity

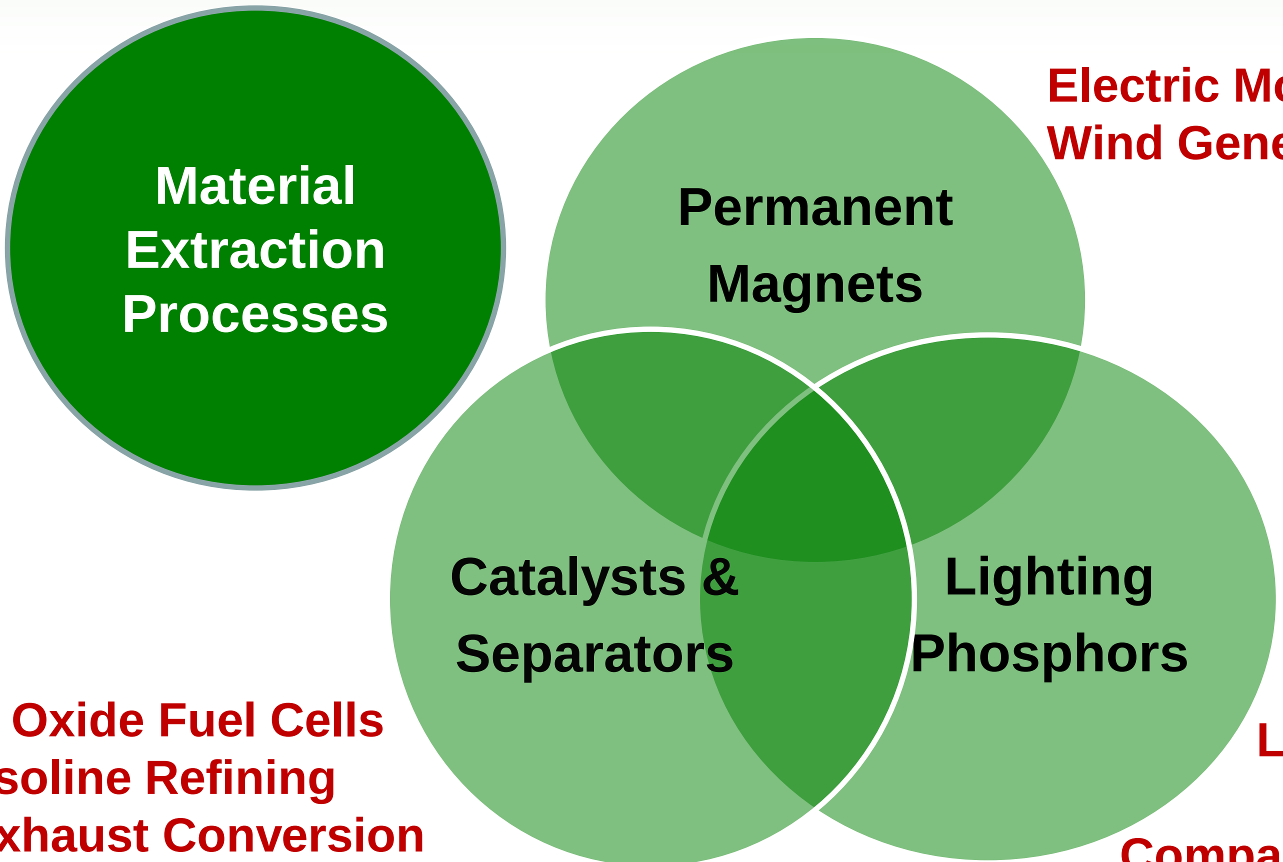
<u>Rare Earth Free Phosphors</u>
Luminscent Nanoparticles without Cadmium



J.Tsao, et.al., *Proc. IEEE* (9/09)

Summary: Critical Materials Technology

Geologic or Recycled Feedstocks



Electric Motors
Wind Generators

Solid Oxide Fuel Cells
Gasoline Refining
Auto Exhaust Conversion

Light Emitting Diodes (LED)
Compact Fluorescent Lights (CFL)

Supply Technologies ⟷ Application Technologies

Questions